QUALITY ESTIMATION OF THE STONEWORK BLOCKS IN BARBAR TEMPLE AND AL-KHAMIS MOSQUE, BAHRAIN

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Abstract

We report on our assessment of the present quality of the stonework blocks in two historic structures in Bahrain: the ancient Barbar Temple and the early medieval Al-Khamis Mosque. The Barbar Temple, located in the village of Barbar, was built around 2000 BCE. Al-Khamis Mosque was built around the 8th century CE. We measured the quality and condition of the stonework blocks in both structures. Our results show that the quality in both structures is fairly good and demonstrate that our quality testing methods are effective for evaluating the quality of ancient and medieval stonework blocks.

1. Introduction

As part of the conservation and restoration work of the Center for the Global Study of Cultural Heritage and Culture, Kansai University (CHC), this study assesses the quality of the stonework blocks at two historic buildings in Bahrain: Barbar Temple (built c. 2000 BCE) and Al-Khamis Mosque (built c. 700 CE). CHC has been carrying out investigations in the Kingdom of Bahrain related to the preservation of cultural heritage sites since 2015. In September 2015, representatives from CHC and representatives from the Bahrain Authority of Culture and Antiquity visited several ancient ruins to discuss plans for their conservation as well as their suitability for continued use. From among these ruins, Barbar Temple and Al-Khamis Mosque were identified as candidates for further study.

Barbar Temple[1)] is the largest archaeological site on the main island of Bahrain. Its initial excavation was conducted in 1954 by Danish archaeologist P.V. Glob, who, in a total of eight surveys, excavated the main temple and the north-east temple, then backfilled these areas after his investigation. Partial re-excavation and maintenance of the main temple were done in the 1970s and 1980s. The results of the initial excavations in the 1950s and 60s were officially published in a 2003 survey report[2)] along with a 2004 supplementary survey by a Danish team[3)]. As the north-east temple was backfilled after its discovery, we can now assess the structural stonework of the main temple only.

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Al-Khamis Mosque[1] is the oldest mosque on the islands of Bahrain and is famous for its two spires. It is said to have been built at the beginning of the eighth century, and it was used until about the 14th century. It became known as Al-Khamis Mosque or Suq al-Khamis Mosque during the 19th century because at that time a Thursday market (Suq al-Khamis) was held beside the then-ruined mosque. The mosque was restored and renovated by the Bahrain government in the 1950s and excavated in the 1980s by a French team who were able to clarify its original floorplan. In the 21st century, it was further excavated by an English team. Now Al-Khamis Mosque is maintained as a historic park and is open to the public, but it is notably crumbling, and the wall surrounding it is also broken. The Bahrain government is developing plans for the construction of a new site museum and renewal of the park.

The authors are researching the condition and quality of the stonework blocks at these two sites in part to collect data that will enable us to develop effective technologies for the preservation and restoration of these and other ruins in future. At each site, we performed a non-destructive quality estimation test on the stonework blocks, then used another non-destructive test to produce a comparative estimation based on our first test results.

2. Quality estimation test of stonework blocks in Barbar Temple

2.1 Barbar Temple

Fig.1 shows an overview of Barbar Temple. Its main part has been classified into areas dating from three periods of construction, Temple I, Temple II and Temple III. Fig.2 shows the present situation of part of the temple. In the present study, the authors measured the predominant frequency of several stonework blocks using a non-destructive device with an impact hammer to estimate the quality of the stonework blocks in general. This method was previously used in the course of the CHC's project in Egypt[4]. The overall quality of the stone-work blocks was not excessively deteriorated, but some of the stonework blocks had been damaged apparently through weathering and deterioration.

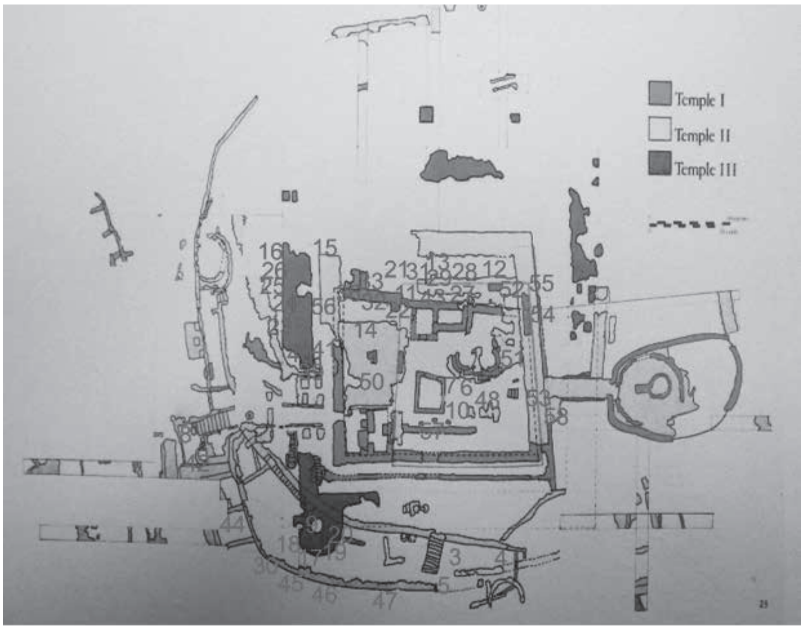

Fig.1 Overview of Barbar Temple

Fig.2 View of one part of Barbar Temple

2.2 Test method

We assessed the quality of the stonework blocks using a commercial frequency and wave type measuring device as shown in Fig.3. When the surface of the object to be tested, in this case, a stone block, is hit by the impact hammer, the resulting wave that travels through the block is detected and recorded by an acceleration sensor and the predominant frequency and shape of this wave are displayed on a monitor. A high frequency of the resulting wave indicates that the surface structure of the stonework block is dense and of high quality, whereas a low frequency indicates that the structure is coarse and of low quality.

Fig.4 shows an example of sensor placement relative to the location of the hammer strike in this test. In the figure, "※" represents the location of the sensor and "×" represents the location of the hammer strike. The distance between the receiving sensor and the location of the hammer strike was about 100 mm in this test.

The numbers in Fig.1 indicate the different places in the temple where we performed our quality assessment. Of these, 8 places were in Temple I, 29 were in Temple II and 14 were in Temple III. We performed the test five times at each location, then calculated the average predominant frequency and standard deviation for each location after excluding the maximum and minimum values.

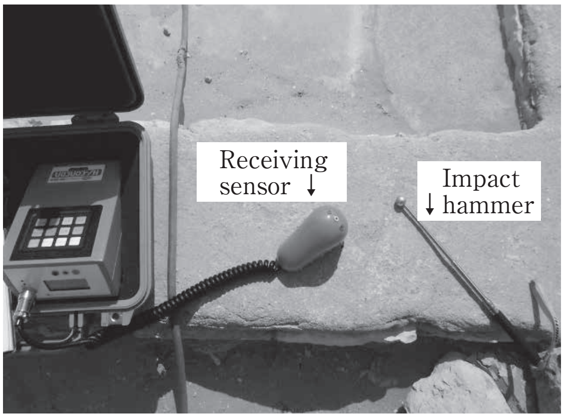

Fig.3 Device for measuring frequency of impact waves

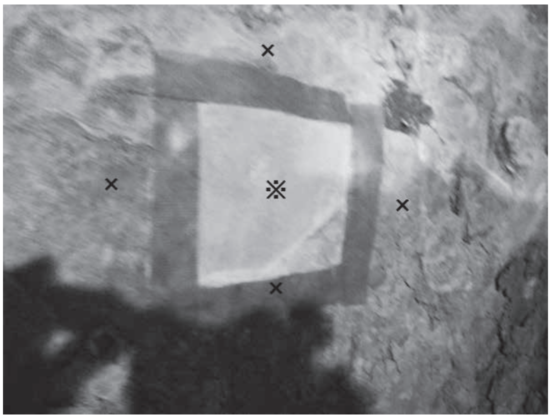

Fig.4 Example of where sensors were placed relative to strike point

2.3 Test results and discussions

Table 1: Impact wave frequency results in Barbar Temple

＜Temple I＞		No.10	No.11*	No.21	No.22	No.32	No.33	No.36	No.57	Average (Temple I)	
Average (Hz)		2,574	4,302	3,372	3,437	2,474	3,398	1,003	2、552	2,889	
SD (Hz)		821	167	507	686	465	261	37	654	450	
＜Temple II＞		No.3	No.4	No.5	No.6	No.7	No.8	No.12*	No.13	No.14*	No.15*
Average (Hz)		2,720	2,920	3,267	3,863	3,882	3,687	831	4,360	4,585	4,239
SD (Hz)		311	490	547	213	296	433	226	55	359	94
No.27	No.28	No.30	No.31	No.42	No.43	No.44	No.45	No.46	No.47	No.48	No.50
4,206	3,906	3,457	3,659	4,271	4,063	3,841	3,665	3,242	3,932	3,711	3,503
112	0	44	66	279	85	296	87	64	217	55	81
No.51	No.52	No.53	No.54	No.55	No.56	No.58				Average (Temple II)	
3,659	4,089	3,959	4,297	2,656	3,945	3,945				3,668	
129	129	176	32	799	721	64				203	
＜Temple III＞		No.9	No.16	No.16*	No.17	No.18	No.19	No.20	No.23	No.24	No.25
Average (Hz)		2,578	3,692	3,965	3,501	3,802	3,659	3,229	3,503	4,023	3,724
SD (Hz)		164	91	121	124	315	66	271	224	64	18
No.26	No.39	No.40	No.41							Average (Temple III)	
4,492	3,229	2,096	2,774							3,448	
139	74	520	139							166	

※SD: Standard deviation

The main test results are provided in Table 1. In Table1, values accompanied by the * symbol are measurements taken on horizontal surfaces while the others are measurements taken on vertical surfaces. Comparing the results from the three construction periods, we found that the average predominant frequency in Temple I was somewhat low and the standard deviation was rather large, casting some doubt on the present quality of the stonework at these locations, but the overall differences between Temple I and the other construction periods were not very large. Because there were some values under 2,000 Hz in the Temple I and II areas, however, the authors concluded that some stonework blocks in these temple areas are of very low quality. Yet even these low-quality stones were not so degraded as to be on the point of failure; in fact, they were in better condition than the near-contemporary stone wall in the underground burial chamber of Mastaba Idout (c. 2360 BCE) in Egypt. Figs.5-8 show some examples of the situation of the stonework blocks that we assessed. The No.36 block shown in Fig.5, which was buried in the soil, generated a low-frequency wave of about 1,000 Hz. The No.12 block in Fig.6 and Fig.7 was an unstable block supported by small stones; when struck, it produced a sound like "poko poko". The No.40 block shown in Fig.8 was located about halfway up an accumulated block wall, some parts of which had been repaired with mortar. These repaired parts generated waves with an average frequency of 1,700Hz, clearly demonstrating the deterionation of the repair materials. Overall, although some individual measurements indicated low quality, the quality of the stonework blocks in Barbar Temple was not very low.

Fig.5 No.36 block in Temple I

Fig.6 No.12 block in Temple II

Fig.7 No.12 block in Temple II

Fig.8 No.40 block in Temple Ⅲ

3. Quality estimation test of stonework blocks in Al-Khamis Mosque

3.1 Al-Khamis Mosque

Fig.9 shows the Al-Khamis Mosque from the front while Fig.10 shows a bird's-eye view. We observed that some stonework blocks had repaired parts and stripping of repaired parts. Overall, the quality of the stonework blocks in Al-Khamis Mosque seems not to have deteriorated excessively.

Fig.9 View of Al-Khamis Mosque

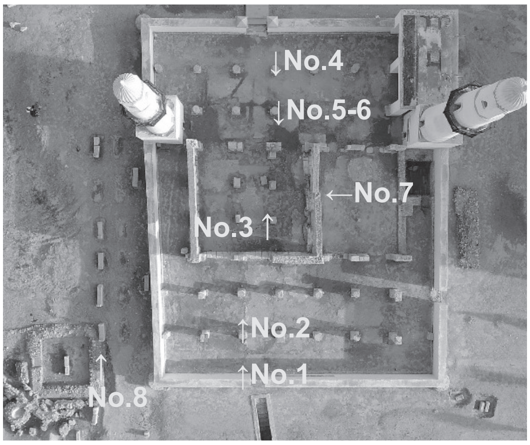

Fig.10 Bird's-eye view of Al-Khamis Mosque (From Prof. Yasumuro)

3.2 Test method

We assessed the stone blocks here using the same non-destructive test and methods that we used at the Barbar Temple. Measurements were taken at eight points and the average predominant frequency and standard deviation was calculated for each point, allowing us to estimate the relative quality of the stone at each point.

3.3 Test results and discussions

Our results are provided in Table 2. The average predominant frequencies indicated that the quality of the stonework blocks in general was not terribly low. In stonework blocks No.4 and No.6, however, the predominant frequency was relatively low, suggesting that the blocks' quality had deteriorated. Figs.11-14 show how the tested blocks were situation. At the place in Fig.14 where a repaired part has obviously been stripped, the predominant frequency was low, indicating that this repaired part had undergone more degradation of quality compared to other stonework blocks.

Table 2 Impact wave frequency results and measured points in Al-Khamis Mosque

Measured points	Situations of the measured points	Average frequency (Hz)	Standard deviation (Hz)
No.1	Horizontal surface at top of 2-stage column	4,131	839
No.2	Horizontal surface at top of 2-stage column	3,880	147
No.3	Horizontal surface at top of 3-stage rectangular column	3,698	230
No.4	Horizontal surface at top of 2-stage column	2,448	863
No.5	Side of repaired part in 3-stage column	3,646	176
No.6	Side of repaired part in 3-stage column (stripped part)	2,083	268
No.7	Floor under arch	4,062	115
No.8	Horizontal surface of bench outside mosque	3,568	187
Total average values		3,439	353

Fig.11 No.4 block

Fig.12 No.5 and 6 block

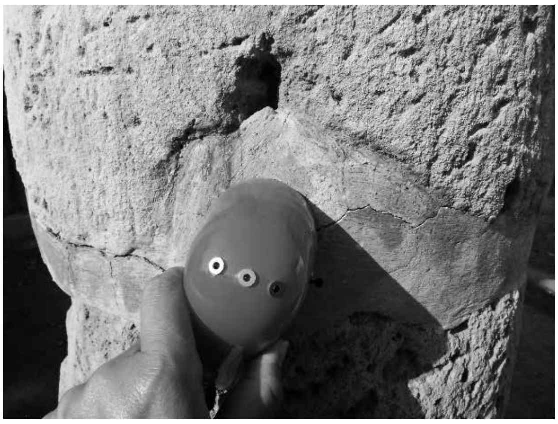

Fig.13 No.5 block (Repaired part)

Fig.14 No.6 block (Repaired and stripped part)

4. Comparative examination of quality estimation test method

4.1 Examination of our test method

The test method that we used in Bahrain required us to compare each block's predominant frequency to the measurements obtained for other stone blocks and thus to assess the blocks' quality relatively. We tested the validity of the results that we obtained using this method by comparing them to the results obtained using other test methods. In this portion of the experiment, we tested the quality of several stone blocks using three methods: the test device shown in Fig.3, a test hammer as shown in Fig.15 and a rebound type hardening meter (RHM) as shown in Fig.16. The test hammer and rebound type hardening meter yielded values measuring strength, such as Young's modulus and deformation coefficient.

Fig.15 Test hammer for rock

Fig.16 Rebound type hardening meter

4.2 Test locations and methods

The locations where we tested all three methods were 26 points on stonework blocks in the Temple II section of the Barbar Temple. The results of the three tests were compared for each point. Figs.17-18 show examples of how we tested the stones using the rebound type hardening meter and test hammer, respectively. The angle of each tested surface was calculated with reference to the vertical. Although measurements with a rebound type hardening meter are usually repeated five times at the same point, our measurements were performed five times at five different points, which meant that the standard deviation was greater than it would have been otherwise. The angle of the test surface was automatically revised when the rebound type hardening meter was used, but when the test hammer was used, the angle of the test surface was measured in terms of the angle of the hammer to the horizontal direction. Each test was repeated three times, and the average value and standard deviation were calculated after the maximum and minimum measured values had been excluded from the data.

Fig.17 Measuring technique with rebound type hardening meter

Fig.18 Measuring technique with test hammer

4.3 Test results and discussions

Figs.19-22 show the relationships among the results of the three test methods. Fig.19 shows the relationship between the average measured values obtained using the rebound type hardening meter and those obtained using the test hammer. Figs.20-22 show the relationships among the three test methods in a plot of all data. Together, the results depicted in our figures show that there was not a strong correlation between the results obtained by the three test methods. There was some correlation between the average values obtained using the rebound type hardening meter and those obtained using the test hammer, but this correlation was not strong. It remains difficult, therefore, to determine which of the three methods is most suitable for quality evaluation of ancient stonework blocks. It must also be noted that our results contain errors related not only to the different test methods but also to variation in the experience of the human testers. Accordingly, we think it is necessary to estimate stone quality with stocking data hereafter.

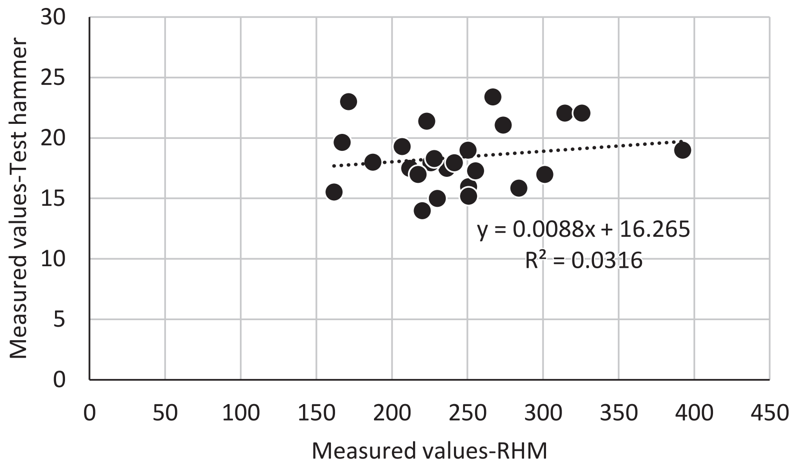

Fig.19 Relationship between values obtained with rebound type hardening meter (RHM) and those obtained with test hammer (average values)

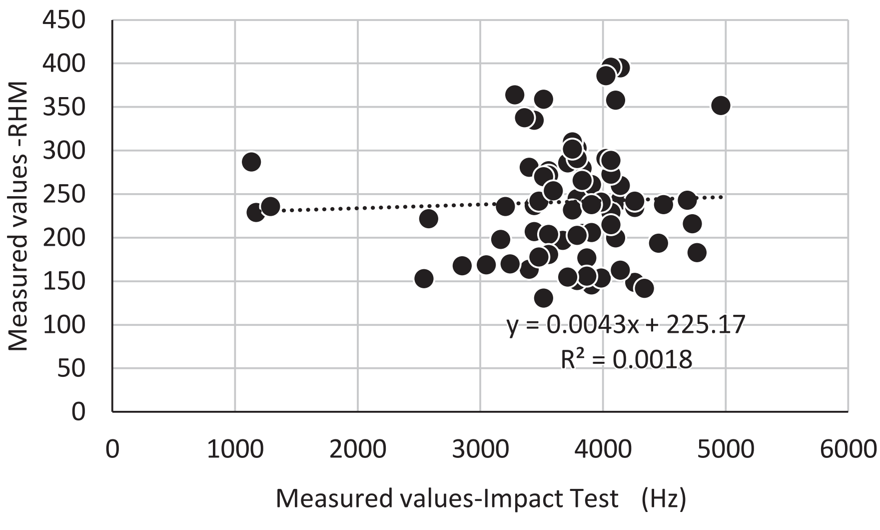

Fig.20 Relationship between values obtained with impact hammer and those obtained with rebound type hardening meter (RHM) (all data)

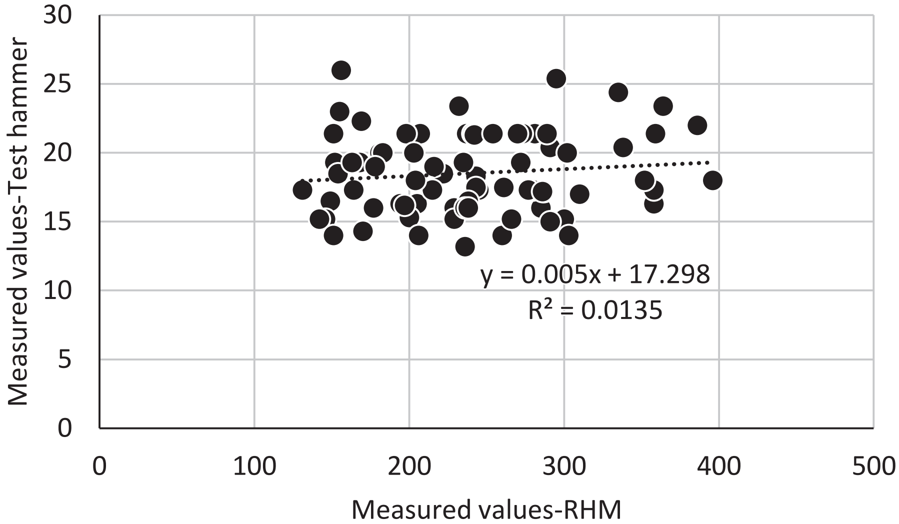

Fig.21 Relationship between values obtained with rebound type hardening meter and those obtained with test hammer (all data)

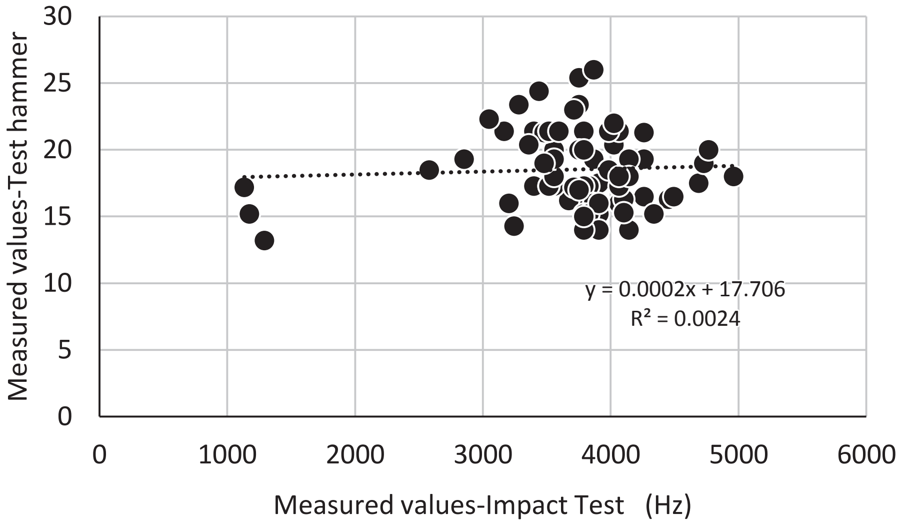

Fig.22 Relationship between values obtained with impact hammer and those obtained with test hammer (all data)

5 Conclusions

(1) We found that, overall, the quality of the stonework blocks had not deteriorated excessively at either the Barbar Temple or Al-Khamis Mosque, based on the results of our impact hammer test. Some individual stonework blocks, however, were possibly of low quality, especially those that had been repaired with mortar and later stripped.

(2) We concluded that the relative quality of ancient and medieval stonework blocks can be estimated using the impact hammer test.

(3) We were not able to determine whether the impact hammer test is superior to other

testing methods using rebound type hardening meters and test hammers, as we found no clear correlation between the results obtained using these three methods. Stocking data should be used hereafter in assessments of the quality of ancient and medieval stonework.

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References

1) Japan Consortium for International Cooperation in Cultural Heritage, Survey Report on the Protection of Cultural Heritage in Bahrain (2012).
2) H. Hellmuth Andersen and F. Højlund, The Barbar Temples, 2 Vols., Moesgaard (2003).
3) F. Højlund, New Excavations at the Barbar Temple, Bahrain, Arabian Archaeology and Epigraphy, 16, 105-128 (2005).
4) Center for the Global Study of Cultural Heritage and Culture, Kansai University, Final Report Comprehensive Global Studies for Conservation and Utilization of Cultural Heritage, 91-100 (2018).